EXPERIMENTAL INVESTIGATION OF EFFECT OF OPERATING CONDITIONS ON PERFORMANCE OF ORC SYSTEM BASED ON OIL FLOODED TWIN SCREW EXPANDER

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ABSTRACT

The paper discusses the following aspects on the experimental investigation of effect of operating conditions on volumetric expander (oil flooded twin screw expander) based ORC system.

- Experimental investigation of oil flooded twin screw expander performance in an ORC system
- Experimental investigation and analysis of oil separator pressure drop and its effect on volumetric/isentropic efficiency of the expander
- Variable speed versus constant speed operation - Effect on isentropic efficiency of expander and cycle efficiency. The variable speed operation gives optimum isentropic efficiency (80 to 85%) at all loads of low potency heat recovery for power generation.
- Field experience of 30 and 100 kW screw expander based ORC system

1. INTRODUCTION

Organic Rankine Cycle (ORC) is emerging as one of the most suitable technology for harnessing low potency (low temperature) heat for electrical power generation.

Currently it is needless to emphasize the importance of harnessing low potency heat since it has become “the need” for any industry. However there are several challenges in harnessing low potency heat (Goel *et al.*, 2014):

- Higher cost of heat recovery due to low logarithmic mean temperature difference (LMTD)
- The conversion efficiency is low as the heat source becomes lower and lower. Although very high isentropic efficiencies of the organic fluid expander/turbines is achieved, the cycle efficiency has always remained low since the limiting Carnot efficiency is itself low at these temperatures.
- Availability of equipment in terms of reliability and uninterrupted operating hours

This paper discusses/reports the investigations carried out in overcoming some of these challenges to make ORC more and more viable. The experimentally investigated ORC system consists of a volumetric expander (oil flooded twin screw expander).

The investigation is based on understanding the mechanical and thermal performance of the ORC system, with respect to thermodynamic parameters of operating fluid and variable conditions of heat source and heat sink. The key experiments investigated are the effect of operating shaft speed on the expander performance at part load conditions and the effect of oil separator pressure drop on performance of the system (Mujic *et al.*, 2010).

The later part of the paper covers the challenges involved to make the ORC technology viable and reliable for various applications (Goel *et al.,* 2014). It also focuses on identifying the key areas of development to make the ORC system cost competitive and reliable in operation.

2. EXPERIMENTAL INVESTIGATION

The ORC experimental facility is designed for testing ORC system and its different components. The system uses low temperature saturated seam (at around 130°C) as the heat source and wet cooling tower (with water cooled condenser) for heat rejection. It is designed to test various capacities of ORC expanders/ turbines from shaft power capacity of 10 to 100 kW. The shaft power is measured by using an eddy current dynamometer (capacity 110 kW). The system is also designed for different operating fluids ranging from HCFC, HFC families to pure Alkanes. The photograph of the test facility is as shown in Figure 1.

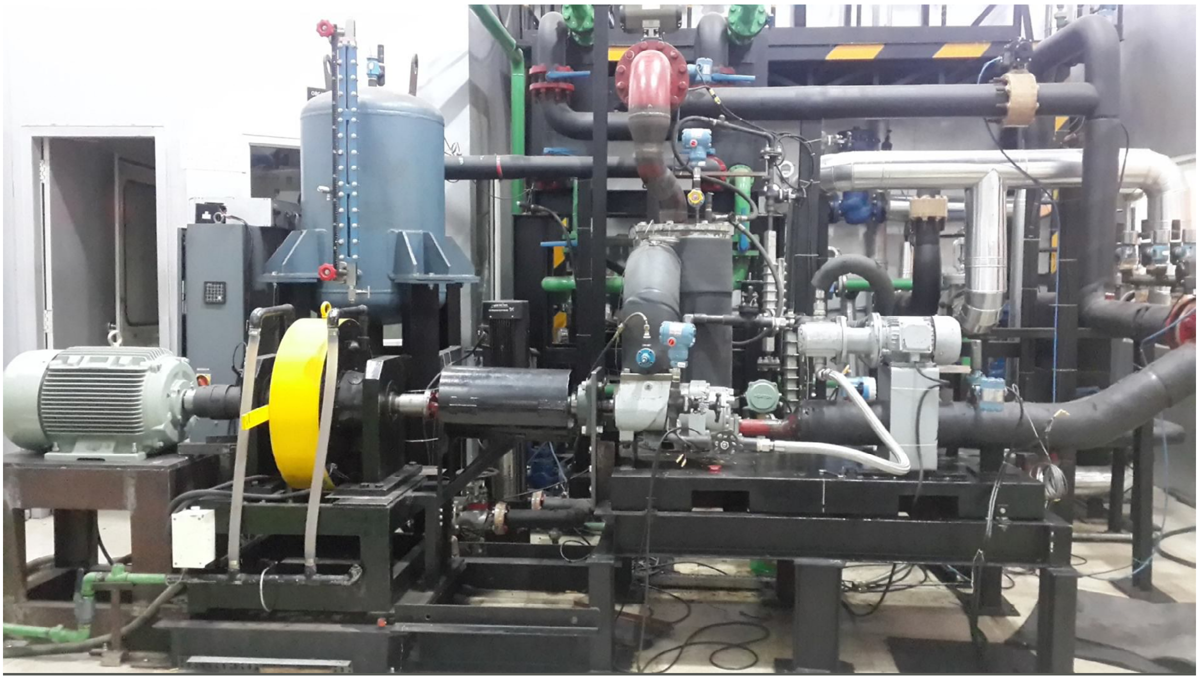

Figure 1: ORC test facility (with screw expander)

The current research work is oriented towards investigation of oil flooded twin screw expander for addressing the parametric performance of twin screw expander. The selected expander is a 4/5 lobe type design with designed displacement volume of 0.00292 m^3 per revolution with volumetric compression ratio of 4.5. The rotor length is 245 mm. The maximum withstanding pressure of the expander casing is 18 bar abs. Hence during operational trials, the expander inlet pressure is limited up to 16 bar abs. The operating fluid used is R245fa (1,1,1,3,3 pentafluoropropane). The expander was tested for variable speed as well as constant speed operation. The variable speed operation was tested in the operating speed range of 1000 to 4500 rpm. The Constant speed operation was tested at 1500, 2000 and 3000 rpm. The experimental investigation was conducted with maintaining a superheat vapor condition (degree of superheat at 20°C) at expander inlet. The lube oil for bearing weas pumped inside the expander using a positive displacement pump with constant flow rate.

Experimental results obtained from the performance testing of the expander operating at a constant shaft speed condition of 1500 rpm and 2000 rpm with steady state heat source and heat sink parameters of full load capacity, are presented in Figure 2 and 3 respectively. The experiments were conducted at steady state conditions of heat sink and heat source. The performance of the expander was monitored at steady conditions of constant flow of cooling water (heat sink fluid) and steam (heat source fluid). The expander performance is observed though the isentropic efficiency of the expander. The isentropic efficiency of the expander is calculated from Equation (1).

$$\eta_{isentropic} = \frac{h_1 - h_2}{h_1 - h_{2'}} \tag{1}$$

The performance of the expander was monitored on the calculated isentropic efficiency based on measured operating parameters of pressure and temperature at expander inlet and outlet.

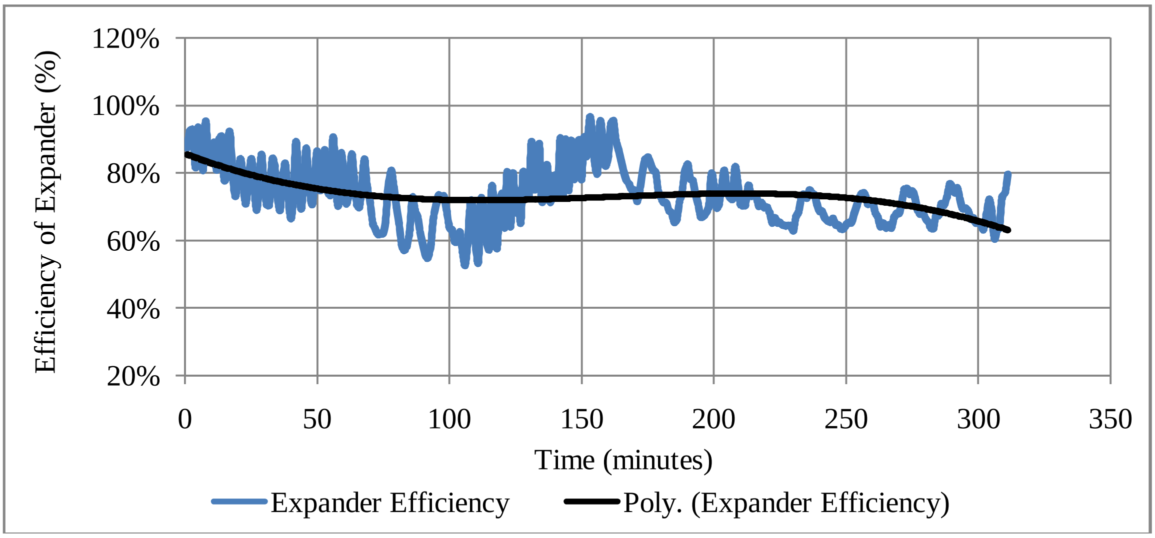

Figure 2: ORC experimental analysis (1500 rpm) **-** Expander isentropic efficiency

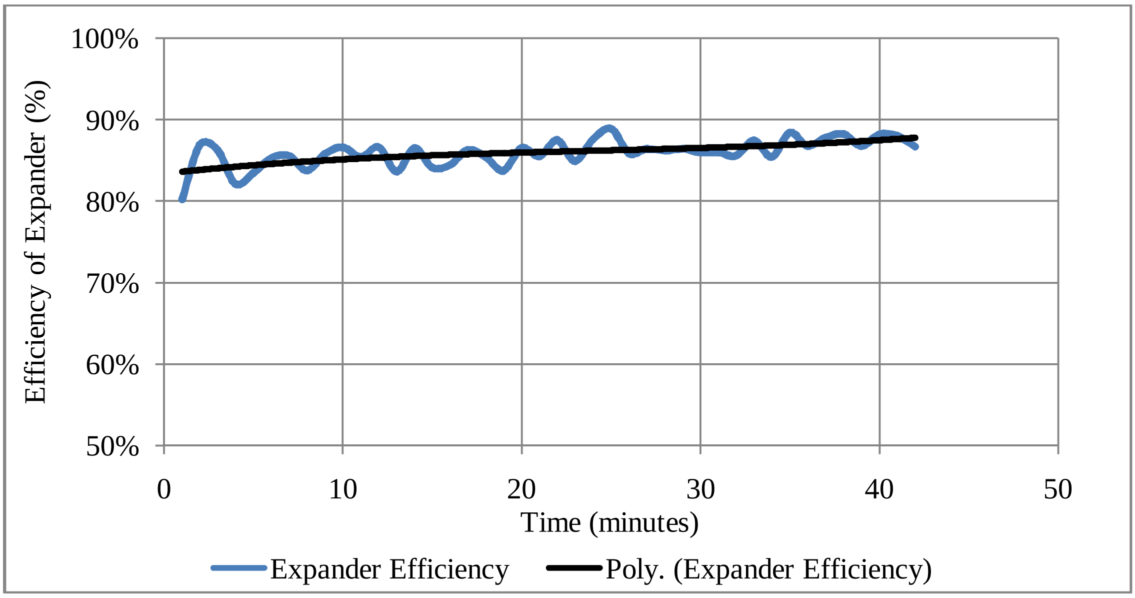

Figure 3: ORC experimental analysis (2000 rpm) **-** Expander efficiency

From Figure 2, it can be observed that the isentropic efficiency of expander operating at constant speed of 1500 rpm was in the range of 60 to 95%. The stable zone of operation indicated the expander isentropic efficiency in the range of 60% to 80%. Similarly from Figure 3 it can be observed that the isentropic efficiency of the expander operating at constant speed of 2000 rpm is in the range of 80% to 88%. This investigation indicates that the isentropic efficiency of the expander increases with increase in shaft speed. The cyclic variations in the isentropic efficiency graph of expander are due to the dynamometer loading and unloading to maintain the expander shaft speed constant and with the feed pump operating to maintain constant degree of superheat at expander inlet.

2.1 Comparison of variable speed versus constant speed operation

In scenarios where heat source is varying (ORC system operating at part load conditions), the ORC system can be operated in two modes: constant speed and variable speed. The impact of operating mode on the isentropic efficiency of expander is experimentally investigated. The tests were conducted for the constant condensing temperature of 40°C (saturation pressure of 2.5 bar abs.) and variable heat input. The system was operated in constant speed mode at 1500 rpm and in variable speed mode. The shaft speed was varying between 1000 to 3000 rpm in variable speed mode operation. The experimental results obtained during this investigation are shown in figure 4.

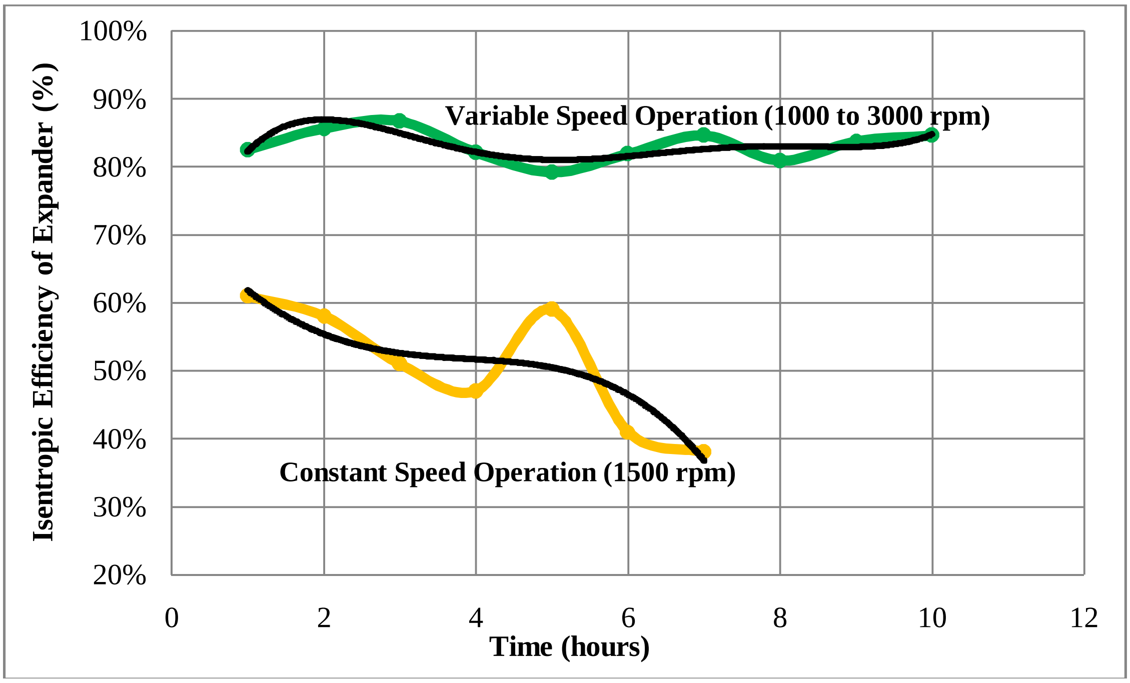

Figure 4: ORC Test result - Constant speed versus variable speed

From Figure 4, it is observed that the isentropic efficiency of the expander started reducing from 60% to less than 40%, at constant shaft speed mode with respect to reduction in heat input. The expander shaft speed was forced to be maintained at 1500 rpm using a dynamometer. The speed was maintained constant by varying the breaking torque on the expander shaft. That resulted in reduction of expander inlet pressure from 14.3 bar abs. to 5.7 bar abs. (expander pressure ratio decreased from 3.58 to 1.43) with respect to heat input reduction from 100% to 30%. The reduction in pressure ratio has resulted in poor expander efficiency.

In variable speed mode, the Shaft was allowed to vary by maintaining constant breaking torque on the dynamometer. The shaft speed variation was resulted by reduction in heat input from 100% to 30% load. The reduction in heat input actually resulted in reduced mass flow of operating fluid (as the pump flow modulated to maintain required degree of superheat at expander inlet). The effect of this change in mass flow resulted in fairly constant expander inlet pressure in the range of 13.6 to 14.3 bar abs. The obtained expander isentropic efficiency in this mode of experiment is in the range of 80 to 85%.

The conclusion drawn from this investigation is that, the operating pressure ratio of the expander impacts the expander isentropic efficiency. Higher pressure ratio is possible in variable speed operation and not is constant speed operation. Hence for part load operations and varying heat input conditions, the performance of the system is efficient at variable speed mode operation and not with constant speed mode operation.

2.2 Effect of oil separator pressure drop

The lube oil is injected inside the oil flooded twin screw expander which is required for lubrication of bearings and for providing the sealing between two helical screws. Majority quantity of lube oil is pumped to the bearings mounted at both the ends of expander shafts (main rotor and gate rotor). A small quantity of lube oil gets mixed with operating fluid inside expander and then provides the required sealing between two screws. After lubrication the oil from bearings also gets mixed with the operating fluid and it comes out from low pressure port along with operating fluid. This oil has to be separated and circulated back to the expander for continuous lubrication and sealing. The oil separator performs the function of oil separation and also provides the required head for lube oil pump. The location of oil separator in the ORC system is between the expander outlet and condenser inlet. It is as shown in figure 5.

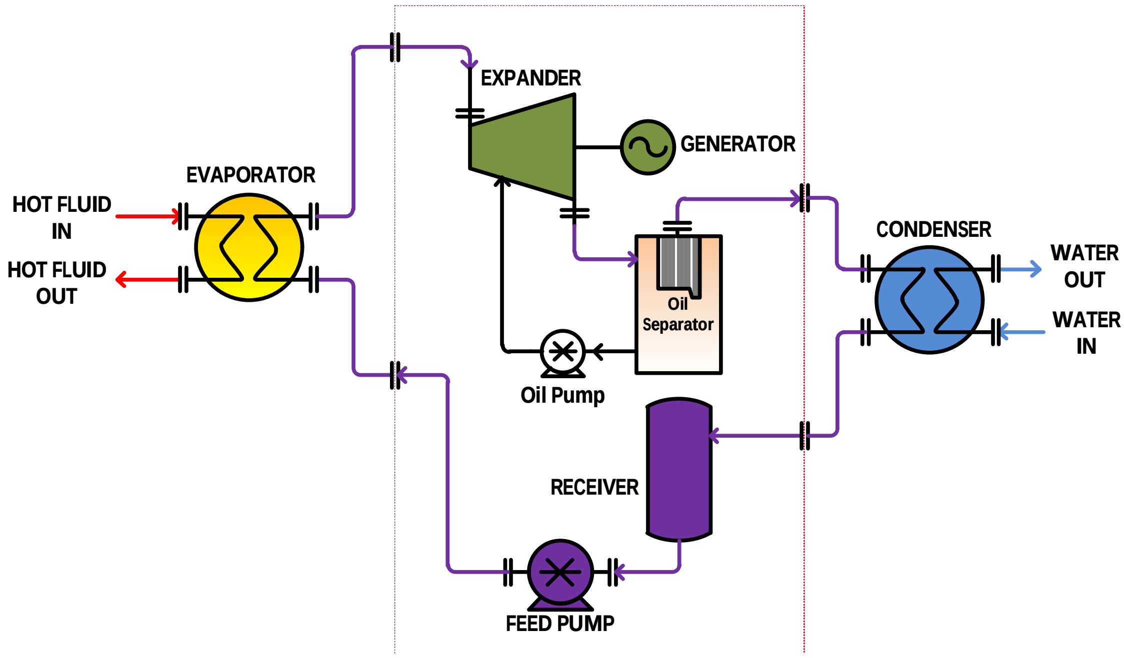

Figure 5: ORC system block diagram (with oil separator)

The oil separator tank is provided with two stage oil separation. In first stage, the bigger droplets of oil are separated by centrifugal action which is supported by the tangential entry of fluid oil mixture coming out from expander. After the first stage separation, the direction of flow is reversed and then the fluid is filtered using a clothed filter element for small oil droplet removal. This filter element is installed in the inner cavity of the oil flow reversal chamber. The smaller oil droplets are captured in the walls of filter element. These captured oil droplets trickle down, and get collected at the inner cavity of the element. Due to these changes in flow direction and filter element, the oil separator has an inherent pressure drop of the process fluid.

The conventional design of oil separator which is used along with screw compressors was incorporated in the experimental investigation. In experimental study the pressure drop observed across the oil separator was in the range of 2.4 to 2.6 bar. This resulted in increased expander outlet pressure (i.e. reduced pressure ratio) which caused reduction in power output from the expander. To decrease this pressure drop and to increase the pressure ratio across the expander, the oil separator inlet and outlet ports along with interconnecting piping was redesigned for low pressure parameters of operating fluid. After redesign, the pressure drop across the oil separator was observed to be reduced by 40%.

The effect of oil separator redesign is experimentally investigated (for improvement in expander efficiency) and compared with the results obtained with original oil separator design. The obtained results are shown in Figure 6. The reduced pressure drop across oil separator resulted in improved expander efficiency by 5%.

The experimental investigation of pressure drop across the oil separator was carried in term of its effect on the isentropic efficiency of the expander while operating at constant condensing conditions which are maintained by constant flow of heat sink and heat source fluid. The experiment was carried out at steady operating conditions of operating parameters across the expander. It was compared with earlier performance of the expander which had higher pressure drop across the oil separator.

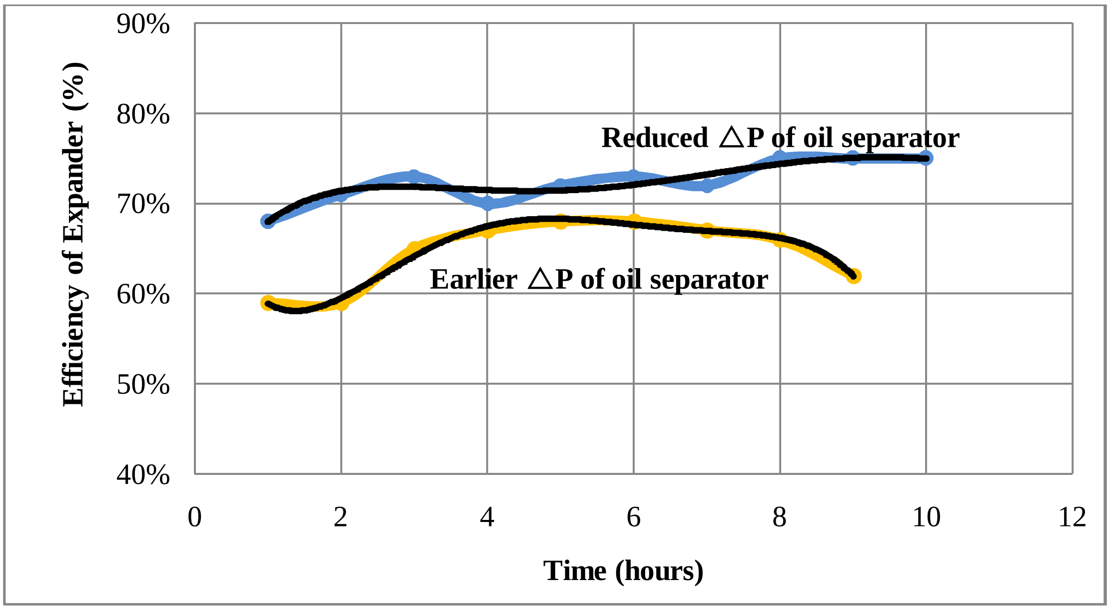

Figure 6: ORC Test result - Effect of oil separator pressure drop

Based on this experimental investigation, it can be inferred that, reduction in pressure drop across the oil separator has reduced the irreversibility from the expander and improved the expander isentropic efficiency. It can also be inferred that removal of oil separator will further enhance the expander efficiency and thus the overall efficiency of the system. This improved isentropic efficiency of expander is effect of improved pressure ratio across the expander as the expander outlet pressure has approached towards the condenser pressure. The higher pressure ratio resulted in increased power output and better efficiency.

However, in the absence of oil separator, the lube oil will be carried over to condenser. The oil carry over to condenser will foul the heat transfer surface. This is not an issue while the ORC system is operating at full load condition, as the oil percentage in operating fluid will be less than 3%. (http://handbooks.swep.net/) But at part load, the oil percentage in operating fluid will be more than 35% which affects heat transfer in side condenser. Therefore it is required to have sufficient over surface area in condenser design. The oil collection and recirculation to the expander also need to be addressed in this case.

2.3 Mechanical performance

Experimental set-up was initially designed with a velocity range of 20 m/s at expander inlet port. However during experimentation, the vibrations were noted at expander inlet piping. The cause of these vibrations was the increased velocity at expander inlet due to convergent nozzle to reduce pipe diameter of 114.3 mm to 60.3 mm neat the inlet port of expander. The nozzle was initially located close to the expander inlet port which did not provide enough straight length of pipe to stabilize the operating flow. The redesign for flow stabilization resulted in reduction of these vibrations and improved the expander reliability.

3. 100 kW PROTOTYPE

The learning from all these experimental investigations of ORC system, are implemented in first prototype of capacity 100 kW, which is under commissioning and testing at a solar thermal based power plant. The photograph of this prototype ORC system is as shown in Figure 7.

Figure 7: First prototype of ORC system: Capacity 100 kW

The key features included are the variable speed operation for part load conditions to keep higher pressure ratio across the expander and improved design of oil separator to get lower expander outlet pressure. The expander inlet flow stabilization is also implemented to reduce the vibration at the expander. The mechanical vibration from the rotary systems i.e. expander and electrical generator are decoupled from each other by implementation of timing belt drive arrangement.

The experimental investigation of 100 kW prototype system are yet to be carried out as the system is under commissioning stage and will be produced in further work to improve the next version of the ORC systems.

4. CONCLUSION

- The ORC system is more efficient at operations with variable speed for varying source heat input and at part load conditions. The isentropic efficiency of the expander at variable speed mode of operation is 80-85%, which is at least 30% higher than that in constant speed mode. The variable speed operation improves the viability of ORC system.
- The redesigned oil separator improved the expander efficiency by 5% due to reduction in pressure drop across it by 40%. Inclusion of any additional component between expander outlet and condenser reduces the expander efficiency as well as cycle efficiency due to the pressure drop across the component.

- The removal of oil separator will certainly improve the efficiency of the system as pressure ratio across the expander. However this will increase the heat transfer area required in condenser. This has to be further investigated to arrive at an optimum system design.
- The performance of the expander was improved by reducing the flow induced vibrations at expander inlet. The availability and reliability of the screw expander for enhanced mechanical performance has to be further investigated by implementing vibration mitigation techniques, shaft seal development and arriving at optimized mechanical design parameters.

NOMENCLATURE

η	efficiency	(%)
h	enthalpy of fluid	(kJ/kg)
N	number	(–)

Subscript

1	expander inlet
2	expander outlet
‘	isentropic condition

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